Anchor Design Affects Dominant Energy Loss Mechanism in a Lamé Mode MEM Resonator

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***Abstract*— We present a Lamé mode resonator whose limiting damping mechanism depends on its anchor geometry. The device is anchor-limited when the anchors are stiffer and is Akhiezer-limited with more compliant anchors. This result is determined by observing the temperature dependence of the quality factor (Q) for devices with different lateral dimensions and different anchor designs. The total measured Q increases by an order of magnitude with the more compliant anchors and reaches a room temperature fxQ product of 2.2 × 10^{13}. We studied the relationship between the device design and the anchor design and the measured Q(T) results to identify the contributions from different dissipation mechanisms. This investigation provides insight into how anchor design affects anchor damping. [2020-0195]**

***Index Terms*— MEMS, MEM resonators, energy loss mechanisms, Akhiezer effect, anchor damping, support loss.**

I. Introduction

MICROELECTROMECHANICAL (MEM) resonators are used in many commercial applications, for measurement of acceleration, rotation, and timing [1], [2]. To make MEM resonators with higher sensitivity and lower phase noise, minimization of energy loss is key. The common mechanisms of energy loss in MEM resonators are thermoelastic dissipation (TED), surface loss (Surface), pressure damping (Gas), phonon dissipation (ph-ph), and anchor loss (Anchor). These contributions sum in reciprocal as the total quality factor:

$$\frac{1}{Q_{Total}} = \frac{1}{Q_{TED}} + \frac{1}{Q_{Surface}} + \frac{1}{Q_{Gas}} + \frac{1}{Q_{ph-ph}} + \frac{1}{Q_{Anchor}}. \quad (1)$$

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A larger quality factor signifies less energy loss. Understanding how resonator design affects each of these contributions is key to maximization of the overall quality factor of a device. For example, it has been shown that TED can be reduced by placing slots in areas of high strain concentration and geometries can be chosen to minimize heat flow [3]. Additionally, resonators can use bulk modes as opposed to flexural modes to decrease TED because a smaller strain gradient occurs during the isochoric, or volume-conserving, motion of bulk acoustic waves [4]. To minimize surface losses, changes in the fabrication process flow of the resonator, which affect resonator design constraints, can be made. Certain etching processes that increase surface roughness should be avoided and high temperature annealing can be used to further mitigate defects in the crystalline structure of the resonator [5], [6]. To minimize gas damping, and more specifically squeeze film damping, the device can be encapsulated at low pressures.

The ultimate limit of the total quality factor is due to the intrinsic phonon-phonon losses within a crystalline structure [7], [8]. For a resonator with a larger mechanical time constant (f^{-1}) than the material thermal phonon relaxation time, phonon-phonon losses are dominated by Akhiezer losses [9]. The stress from device motion alters the local equilibrium of thermal phonons and as they re-equilibrate, entropy increases and energy is dissipated. All devices in this study operate near or in the Akhiezer-limited regime. The energy loss due to this phenomenon is estimated as [7]

$$Q_{AKE} = \frac{\rho c_D^4}{T\gamma^2\kappa\omega} \quad (2)$$

where ρ is density, ω is the resonant frequency of the device, c_D is the Debye velocity, γ is the average Grüneisen parameter and κ is the thermal conductivity.

Ultimately, it is desired to build MEM resonators limited by this material limit, as it will result in the highest achievable quality factor. By fabricating bulk-mode resonators with low TED in the Epi-Seal process, where annealing and encapsulation steps reduce surface loss and gas damping, these loss mechanisms can be suppressed, allowing us to focus on the mitigation of anchor loss [10].

Previous analytical work has shown that increasing the beam aspect ratio and the size of the substrate can decrease anchor loss in clamped-clamped and clamped-free beams [11]–[13]. For more complicated resonators, finite element models are used to estimate anchor loss where a mathematical layer is employed to absorb any reflected waves, called Perfectly

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Matched Layer (PML) [14]. However, the PML method can deviate from experimental values due to unaccounted sources [15]. In cases such as ours, the wavelengths associated with propagating modes exceed the dimensions of the die; therefore models like the PML model should not be expected to provide accurate predictions. Thus, it is important to use validated measurements of Q_{anchor} to compare with models to ensure all important sources are accounted for when modelling future resonators.

Previous work on anchor geometry in bulk mode resonators has concluded that positioning anchors at in-plane nodal points, places of minimum displacement, can reduce anchor loss [16]. The in-plane aspect of anchor design is desired because the potential of anchor mismatch in fabrication is much higher in out-of-plane anchor types [15]. Recent works have presented phononic crystal anchors and layers with bandgaps that match resonator resonant frequency in order to reflect energy back into the resonator thereby decreasing anchor damping [17]–[20]. We present work where the dimensions of the device and substrate are smaller than the acoustic wavelength in silicon, and the dimensions of the anchoring structures are far smaller than these wavelengths.

At these larger wavelengths, previous work has shown that a decrease in stored energy in the tethers relative to the stored energy of the device can decrease anchor damping as long as the resonant frequency of the tether does not approach that of the device itself [21], [22]. This effect can only be visible in devices that are anchor limited [23]. In this work, we carried out experiments on resonators with two distinct anchor designs as shown in (Figure 1a).

This work builds on previous work in measuring and identifying sources of damping in MEM resonators [24]–[26]. We measure the quality factor over temperature, and have identified temperature profiles of thermoelastic dissipation (TED) and air damping, allowing us to establish the presence or absence of these effects in our devices. Prior work has shown that phonon dissipation in the Akhiezer region ($Q_{ph-ph} = Q_{AKE}$) is detectable in MEM resonators [27].

In this work, we present direct measurements of anchor damping and the Akhiezer effect in Lamé-mode resonant MEMS. Two anchor geometries for the same device are compared. The Q of the stiffer 'standard' anchor geometry is limited by anchor damping, where as the Q of the more compliant 'springy' anchor geometry is an order of magnitude larger and reaches the f×Q Akhiezer limit for single crystal silicon (Fig. 1 and 2). We compare the two anchor geometries in two device sizes: 320μm and 400μm (11.8 and 10 MHz respectively), and show that the measured Q(T) for the springy anchor devices is consistent with amplitudes and scaling expected for Akhiezer damping.

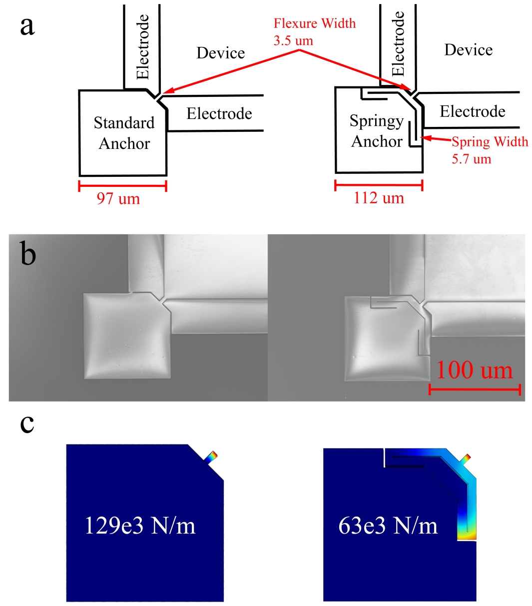

Fig. 1. 400μm by 400μm Lamé-mode devices tested in this article. a) cartoon of the standard and springy anchor, b) SEM of the standard and springy anchor, and c) finite element model of deflection of standard and springy anchor with respective spring constants.

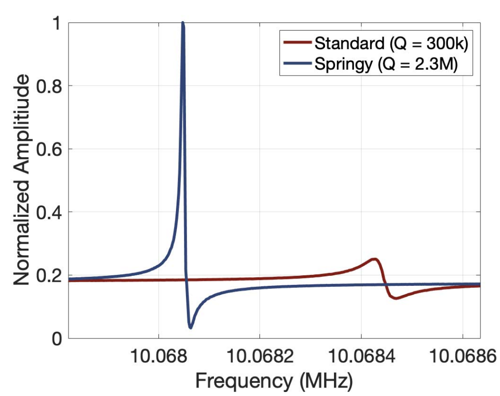

Fig. 2. Room temperature frequency sweeps of standard and springy 400μm by 400μm Lamé-mode resonators spaced 400Hz apart. Anti-resonant peaks are caused by feedthrough capacitance.

II. Fabrication and Design

These devices are fabricated with an etch hole-free variant of the Epi-Seal process. They are encapsulated at a pressure between 0.1 to 1 Pa and are free of native oxide [10], [28]. By omitting the wafer-bonding step and inserting a new venting step, the yield of this etch hole-free variant is increased when top of the line wafer bonding tools are not available.

In this process, we start with a (100) SOI with a 2μm device layer and release the bulk of the square mass with vapor hydrofluoric acid (Fig. 3a and b). The Lamé mass is not fully released with its edges remaining attached to the buried oxide. We then grow the device layer to 40μm with doped epitaxial silicon (Fig. 3c). The vent holes from

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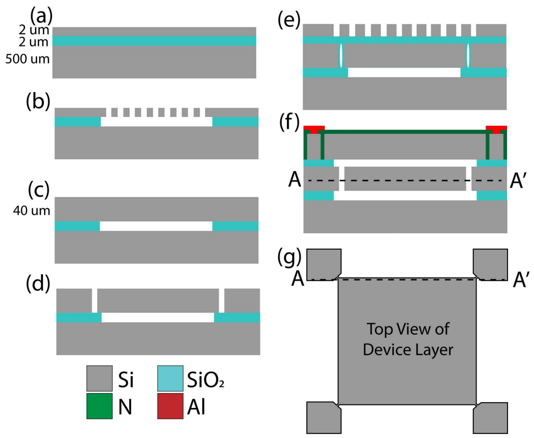

Fig. 3. Fabrication steps of etch hole-free Epi-Seal process, not to scale. (a) started with a boron-doped SOI, (b) bulk of Lamé mass is released, (c) etch holes sealed and device layer grown to 40μm with epitaxial silicon, (d) device geometry etched with DRIE, (e) trenches and top of device layer filled with TEOS oxide and covered with epitaxial silicon cap, (f) devices fully released with final encapsulation and electrical via formation, and (g) the top view of the device layer from (f).

the previous step are sealed during this step due to silicon migration at 1100° C [29]. To form the geometry of the Lamé device and its electrodes, the device layer is etched with Deep Reactive-Ion Etching (DRIE) with a 40:1 ratio (Fig. 3d). Conformal tetraethyl orthosilicate (TEOS) oxide is deposited in the trenches and on top of the device layer. The oxide layer is then covered with the first encapsulation layer of epitaxial silicon (Fig. 3e). Finally, the devices are fully released with vapor hydrofluoric acid and covered by the final cap layer. Vias to electrodes are etched through the cap and isolated from the rest of the cap with nitride (Fig. 3f).

The end result of this process is a stack that includes a 30μm polysilicon cap layer, a 40μm single crystal silicon device layer, and a 500 μm single crystal silicon handle layer with 2μm of silicon dioxide between each layer. The boron doping concentration of the device layer is $2.2\times10^{20} cm^{-3}$.

We designed these Lamé mode resonators to have good yield in this fabrication. The standard anchor resonator has yielded well in this process with a simulated stiffness of 129×10^3 N/m. Designing longer and thinner tethers to decrease anchor stiffness could result in device failure or severe over-etch due to the 40:1 DRIE process. Thus, we designed a folded beam ('springy') structure to reduce anchor stiffness by 50% to 63×10^3 N/m. The 400μm and 320μm devices have the same anchor dimensions in both the standard and springy designs.

III. Experimental Method

In order to determine the contributions from anchor damping and Akhiezer damping, we measure the quality factor over a temperature range of 90K to 300K. After cooling down the device to 90K using liquid nitrogen, we measure Q(T) for 5 hours as it warms up to room temperature. Q is measured using the ringdown method, illustrated in the bottom left of Fig. 5 because of its high accuracy. Each device is driven at resonance by a phased-locked loop in a Zurich Instruments HF2LI lock-in amplifier with output signal through a transimpedance amplifier (TIA).

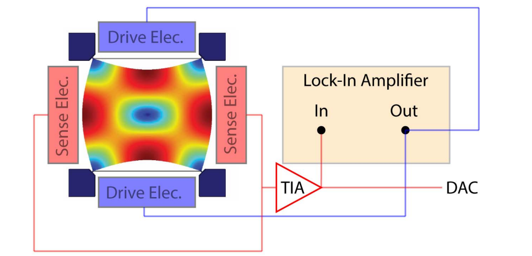

Fig. 4. Each device is capacitively driven and sensed at resonance in closed-loop by a lock-in amplifier. The current from the output of the device is converted to a voltage and amplified by a TIA.

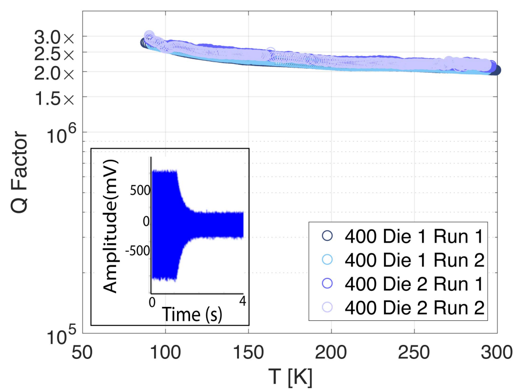

Fig. 5. Q over temperature of 400μm springy anchor Lamé-mode devices from different dies showing consistency in quality factor over temperature. Each point represents quality factor determined from a ringdown, exemplified in the lower left corner.

IV. Experimental Results

We measured Q(T) profiles of Lamé resonators with in plane dimensions of 320μm × 320μm and 400μm × 400μm, each with standard and springy anchors. All four resonators reside on the same 2mm × 2mm die. Multiple dies were tested.

A. Repeatability

Initially, we performed ringdown measurements over the temperature range of 90K to 300K of a springy 400μm Lamé on two separate die to establish the repeatability of these results, as shown in the Q(T) profiles in Fig. 5. We see that

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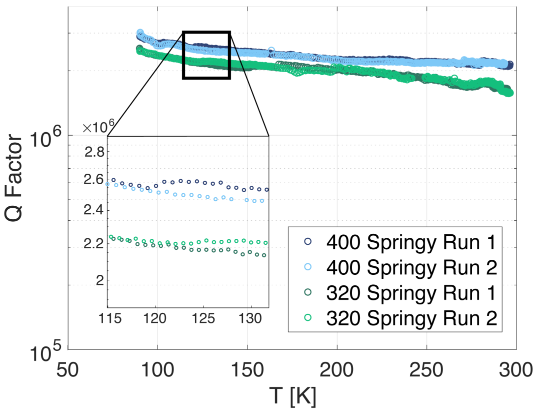

Fig. 6. Q over temperature of $400\mu m$ and $320\mu m$ springy anchor Lamé-mode devices from the same die.

the measured Q(T) is very consistent from measurement to measurement of the same device, where the difference between measurements is within the error of a single measurement (2%). Between a pair of nominally-identical devices from different die, agreement within 5% is observed. Therefore, the overall signal to noise ratio and repeatability between measurements allows us to discern the limiting damping mechanism of this resonator.

The quality factor of the springy $400\mu m$ Lamé resonators in Fig. 5 show a weak but not insignificant temperature dependence. This temperature dependence is inconsistent with the expectation that anchor damping should be independent of temperature. Since anchor damping is affected by geometry, the slight temperature dependence in elasticity and volume (thermal expansion) is negligible. For anchor limited devices with very small quality factors, the temperature dependence of stress is apparent in Q(T) profiles [30]. However, the magnitude of the measured quality factors of all devices in this article are large enough where small changes in stress due to temperature change are negligible. The absence of a peak in measured quality factor at 120K (where the coefficient of thermal expansion (CTE) of silicon is 0) suggests that TED is not important for these devices [31]. Additionally, COMSOL simulation predicts Q_{TED} to be $>1\times10^8$, which is much higher than the all measured Q values. The weak temperature dependence is inconsistent with a pressure damping contribution [25].

B. Device Size

The quality factor of the springy $320\mu m$ device exhibits a very similar temperature profile as that of the $400\mu m$ device (see Fig. 6). To assess the limiting damping mechanism, we compare this data to the estimate of the Akhiezer limit over temperature in Fig. 7a. This estimate accounts for temperature dependence of parameters in Equation 2, as well as the difference in resonant frequencies between this pair of devices [32], [33]. We see that the $f\times Q$ product is the same for these two designs. Included in this figure are estimated minimum and maximum bounds of the Akhiezer limit arising from the minimum and maximum Debye velocities in silicon [34]. This estimate also accounts for the fitting of the Grüneisen parameter, γ, for the Lamé mode in bulk-mode resonators [27], [35], [36]. Measured Q(T) for the springy anchor designs of both device sizes fall within the bounds of the estimated Akhiezer limit, and the $f\times Q$ measurements match over temperature. Therefore, we conclude that the springy Lamé-mode resonators in this work are dominated by Akhiezer damping.

C. Anchor Design

Fig. 7b and c compare the Q(T) of standard anchor resonators to that of the springy anchor resonators from the same encapsulated die for $400\mu m$ and $320\mu m$ devices respectively. The Q(T) of the standard $400\mu m$ device is 8X lower than that of the springy device and is independent of temperature, as we expect of anchor-limited resonators. With the lack of peak in Q(T) at 120K in conjunction with the simulated Q_{TED} of the standard Lame resonator $>1\times10^8$, TED can be eliminated as the limiting damping mechanism. These devices were tested on the same encapsulated die and thus have identical material properties, pressure, stress, and fabrication process parameters (i.e. etch profile). Therefore, the change in the anchor design must be the cause of the 8X decrease in Q between these designs. Similarly, for the $320\mu m$ standard device, the change in anchor design can be attributed to the 10X reduction in Q. Now that we can rule out Akhiezer damping, pressure damping, surface damping, and TED as the limiting mechanism with the addition of temperature independence in Q(T), we conclude that the devices with the standard anchors are anchor damping limited.

Using the simulated Q_{TED} and estimated Q_{AKE}, from (2), we estimate the Q contribution from anchor loss of the standard anchor Lamé to be 339k. We cannot estimate anchor loss of the springy anchor Lamé from experimental values because extraction of this contribution depends too strongly on the exact strength of the contribution from Akhiezer loss. However, even given this uncertainty, the Q_{Anchor} of the springy anchor Lamé must be greater than 2.6M. Thus, the change in anchor design decreases anchor loss by at least one order of magnitude.

From these results, we verified that the in-plane compliance affects the amount of anchor damping as found in previous work with strong evidence of standard anchor resonators being anchor limited [21]. For springy anchors with larger in-plane compliance, we observe an approximate 10X suppression of anchor damping, leading to the emergence of Akhiezer damping in these devices.

V. Finite Element Analysis Comparison

We carried out simulations of anchor loss of these Lamé-mode resonators using the finite element analysis (FEA) tool available within COMSOL Multiphysics with a Perfectly Matched Layer (PML) to absorb any radiated energy from reflecting back into the resonator. PML-based simulations

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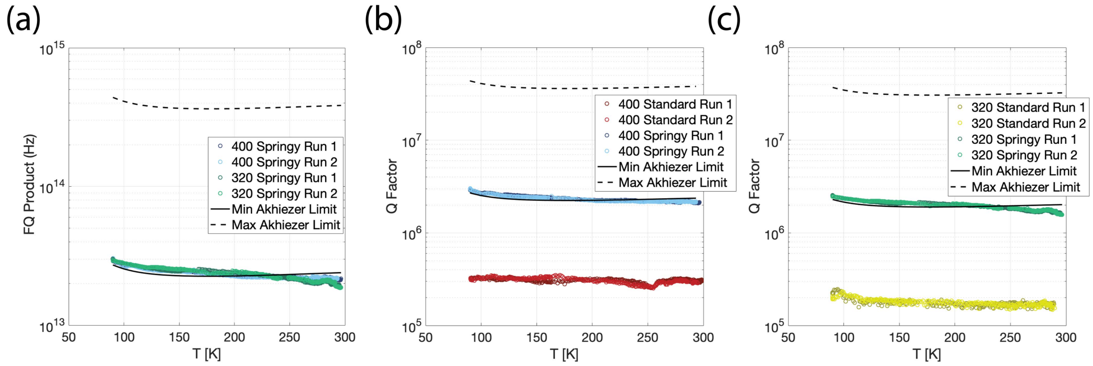

Fig. 7. (a) fxQ product over temperature of 400μm and 320μm springy anchor devices from same die with estimate of Akhiezer limit range over temperature, (b) Q over temperature of 400μm standard vs. springy anchor Lamé-mode devices. Q of standard anchor device is smaller by a factor of 8, and (c) Q over temperature of 320μm standard vs. springy anchor Lamé-mode devices. Q of standard anchor device is smaller by a factor of 10. The solid and dotted black lines represent the estimation of the Akhiezer limit using the minimum and maximum Debye velocities in (2).

have been used by others to model and understand anchor damping for bulk-mode resonators with frequencies above 100 MHz. An important factor to keep in mind with these simulations is that the resonant frequency of all our devices is near 10 MHz. The wavelength for the longitudinal mode in silicon at these resonant frequencies exceeds the thickness of the die that these devices are built in. Therefore, there is no way to place the PML boundary in a physically realistic location. Nevertheless, we carried out PML simulations using a wide range of values for other available parameters in the model, and found predictions ranging from 1×10^8 to 1×10^{11} for the standard anchor and from 1×10^{10} to 1×10^{14} for the springy anchor. All of these PML-model predicted values for Q significantly exceed all our measured values for Q for all designs and all temperatures. We attribute this significant over-estimate of the Q associated with anchor damping from the PML models for these devices to the inability to properly represent the physical structure of our device and surrounding die and other interfaces. Therefore, we are not relying on these PML model results for our claims about the dissipation mechanisms observed in these devices.

VI. Conclusion

We present a verified case where a single device can be limited by anchor damping or Akhiezer damping, depending only on the design of the anchor. For the device with compliant ('springy') anchors that are Akhiezer limited, we quantitatively establish the contribution from Akhiezer damping, including the temperature dependence, which will aid in identifying and modeling the temperature dependence of the terms that contribute to Akhiezer damping. For the devices with stiff ('standard') anchors, that are dominated by anchor damping, we confirm the temperature-independence of the anchor damping mechanism and will initiate a study of the dependence of anchor damping for this mode in this device on the geometric design of the standard anchor.

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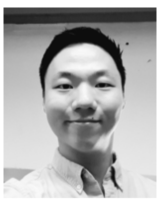

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